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Investigation of detonation characteristics of various fuels

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INVESTIGATION OF THE
DETONATION
CHARACTERISTICS
OF VARIOUS FUELS

BY
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INVESTIGATION OF THE DETONATION
CHARACTERISTICS OF VARIOUS FUELS

by

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Submitted in Partial Fulfillment of

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Master of Science

in

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Cambridge, Massachusetts,
June 1, 1946.

Professor George W. Swett,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

Dear Sir:

A thesis entitled "INVESTIGATION OF DETONATION CHARACTERISTICS OF VARIOUS FUELS" is herewith submitted in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

SYMBOLS

F/A	Fuel-air ratio $\mathring{M}_f/\mathring{M}_a$.
f	Equivalent weight in pounds applied to dynamometer torque arm.
l	Engine stroke, inches.
L	Brake load torque arm length, inches.
mep	Mean effective pressure, psi.
imep	Indicated mean effective pressure, psi.
bmep	Brake mean effective pressure, psi.
$\mathring{M}_a$	Air consumption, lb/min.
$\mathring{M}_{ac}$	Corrected air consumption, lb/min.
$\mathring{M}_f$	Fuel consumption, lb/min.
N	Revolutions per minute.
P_0	Ambient air pressure, in. hg or mm. hg.
P_1	Orifice inlet air pressure, in. hg.
ΔP_1	Orifice inlet air pressure difference, $P_1 - P_0$, in. hg.
ΔP_2	Orifice pressure drop, in. water.
P_3	Inlet manifold pressure, in. hg.
P_{3c}	Corrected inlet manifold pressure, in. hg.
ΔP_3	Inlet manifold pressure manometer difference, $P_3 - P_0$, in. hg.
P_4	Inlet oil pressure, psi.
ΔP_5	Exhaust pressure manometer difference, $P_5 - P_0$, in. hg.
S_1	Micrometer vernier reading of cylinder height, inches.

SYMBOLS
(Cont'd)

S_2	Rotameter reading of fuel flow rate, units.
S_3	Brake load manometer reading, in. hg.
S_4	Engine revolutions per minute.
S_5	Spark advance, degrees.
T_0	Ambient air temperature, $^\circ$F.
T_1	Orifice inlet temperature, $^\circ$R.
T_2	Jacket cooling water temperature, $^\circ$F.
T_3	Fuel-air mixture inlet temperature, $^\circ$F.
T_4	Oil inlet temperature, $^\circ$F.
T_5	Fuel inlet temperature, $^\circ$F.
V_d	Engine displacement, cu. in.
X	Heavy spring, 200 lb/in^2.
W	Counterbalance weight added to brake load torque system, lb.

INVESTIGATION OF DETONATION CHARACTERISTICS OF VARIOUS FUELS

SUMMARY

In this investigation, the detonation characteristics of four fuels were determined in terms of curves of iso-det lines of indicated mean effective pressure against compression ratio and inlet manifold pressure against compression ratio to show the effect of the detonation characteristics of the fuels on engine performance. The four fuels selected, iso-octane, di-isobutylene, triptane, and ethyl benzene, were chosen to best cover the present reference fuels and possible future fuels to be used in high performance aircraft.

It was necessary to limit the scope of the investigation by keeping the following engine operating variables constant: engine RPM, fuel-air ratio, inlet fuel-air mixture temperature, jacket cooling water temperature, and exhaust back pressure. The fuel-air ratio selected for each fuel was at the best power of that fuel. It should be noted that varying the above constants will have a marked effect on the detonation characteristics of the fuels.

The results of this investigation indicated the following conclusions:

1. All four fuels tend to detonate more as: (a) the inlet manifold pressure is increased; (b) the indicated mean effective pressure is increased; and (c) the compression ratio is increased.

2. Iso-octane is the most sensitive to changes in inlet manifold pressure, indicated mean effective pressure and compression ratio.

3. Triptane, di-isobutylene, and ethyl benzene have approximately the same sensitivity to changes in inlet manifold pressure, indicated mean effective pressure, and compression ratio.

4. Triptane is superior to the other three fuels in anti-detonation characteristics.

5. Triptane, di-isobutylene, and ethyl benzene show a marked family similarity in their detonation characteristics.

This investigation was performed at the Sloan Automotive Laboratory, Massachusetts Institute of Technology, during the months of March, April, and May 1946, by Lieut-Comdr. Neil E. Harkleroad, U.S.N., and Lieut-Comdr. Paul W. Gill, U.S.N.

INVESTIGATION OF THE DETONATION CHARACTERISTICS OF VARIOUS FUELS

INTRODUCTION

The fact that detonation, or knocking, of various fuels in a gasoline engine is a function of more than a dozen operating variables has caused great difficulties in detonation research in the lack of an absolute basis of comparison of data obtained in the many methods used in testing and rating of fuels and engines. Many investigations of the detonation characteristics of various fuels have been made in the past with the intention of showing the effects of some particular variable or variables. However, no one investigation shows a comprehensive picture of detonation characteristics of the fuels covered by this report in terms of the overall engine variables and performance, indicated mean effective pressure, inlet manifold pressure, and compression ratio. Considerable difficulties are encountered in any attempt to correlate the data of past investigations, due to the numerous variables, to obtain such a picture. It is the purpose of this investigation to establish the detonation characteristics of four fuels in terms of iso-det lines of indicated mean effective pressure against compression ratio, and inlet manifold pressure against compression ratio in order to show easily the effect of the detonation characteristics of the four fuels tested on maximum engine performance.

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The selection of the four fuels was made to best cover the present reference fuels and the possible future fuels to be used in high performance aircraft. The selection was limited in the number of such fuels available. Iso-octane, an iso-paraffin and the present basic standard reference fuel, was selected to furnish a basis for comparison of the results. The other fuels selected were as follows: di-iso butylene to show the characteristics of a lower grade olefin; triptane to represent the characteristics of a higher grade paraffin; and ethyl benzene to represent the characteristics of a prospective new fuel of the aromatic series.

It was necessary to limit the scope of the investigation by keeping the following engine operating variables constant: engine R.P.M., fuel-air ratio, inlet fuel-air mixture temperature, jacket cooling water temperature, and exhaust back pressure. The fuel-air ratio selected for each fuel was the best power ratio. It should be noted that varying any of the above constants will have a marked effect on the detonation characteristics of the fuels. Although in this investigation no attempt was made to show the effect of the variables kept constant, the results to be obtained may indicate what the future engine designer can expect in engine performance by changing either the compression ratio, the fuel, or both.

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The constant conditions were determined by consideration of the present and probable future standards of fuel and engine

rating tests. It is intended that the procedure methods and apparatus used in the investigation be readily adaptable to present available laboratory equipment and to future investigations of other potentially useful fuels with the possibility of showing a simple method of improving the present aircraft engine performance.

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DESCRIPTION OF APPARATUS

A general overall description of the setup and apparatus is shown in Figs. 1 and 2.

FUELS

This investigation was conducted with the following fuels: iso-octane, di-isobutylene, triptane, and ethyl benzene. The iso-octane was a standard Reference Fuel F, batch No. 6, S specification with octane No. 99.8; and it was obtained from Shell Oil Company. The di-isobutylene was obtained from Stanco Distributors, Inc., under designation of "Reference Fluid SR-10." Index refraction tests indicated that this fluid consisted of

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This investigation was conducted with the following fuels: iso-octane, di-isobutylene, triptane, and ethyl benzene. The iso-octane was a standard Reference Fuel S, Batch No. 4, a specification with octane No. 99.8; and it was obtained from Shell Oil Company. The di-isobutylene was obtained from Enjay Distributors, Inc., under designation of "Reference Fluid DB-10."* Index refraction tests indicated that this fluid consisted of

80 percent 2-4-4 tri-methyl pentene -1 and 20 percent 2-4-4 tri-methyl pentene -2. The triptane, 2-2-3 tri-methyl butane, was obtained through the courtesy of the General Motors Laboratory. The ethyl benzene was obtained from the Dow Chemical Company.

ENGINE

The engine was a C.F.R., high speed, single cylinder, water cooled, variable-compression ratio engine of 3.25 inch bore and 4.5 inch stroke. The engine was equipped with an aluminum piston and sodium cooled exhaust valve. To prevent variation in spark advance, a special breaker mechanism was directly coupled to crank shaft. This mechanism is described in Ref. 1. The spark plugs used were B.G. 157 and Auto-Lite B-3.

FUEL SYSTEM

The fuel system is shown in a schematic diagram, Fig. 3. The fuel was taken from the fuel tank, through a small electrically driven pump to a bubble separator and surge tank, and from surge tank through rotameter and then through two manually controlled needle valves to the vaporization tank. The fuel flow was measured by a Fisher and Porter rotameter which had been previously calibrated by Professor W. A. Leary. The calibration charts were checked before the runs were started.

The fuel system surge tank was found necessary when operating the engine in order to maintain a uniform and controllable flow rate,and to separate any bubbles in the fuel. The first surge tank of lucite was attacked by ethyl benzene and had to be replaced by a brass tank with boiler type sight gage. The surge tank pressure was maintained at about 90 inches of mercury.

AIR SYSTEM

The air system with gages and thermometers is shown in a schematic diagram, Fig. 3. The air could be taken in through an atmospheric duct or through a laboratory supercharger line with the atmospheric valve being used as a bleed valve. The supercharged air was supplied by a Nash blower giving saturated air at 65 degrees Fahrenheit. The air was metered through a flat plate orifice with a flange tap and a .515 inch orifice constructed according to ASME specifications. The air passed from the orifice through a surge tank, through a throttle valve, to the vaporization tank.

VAPORIZATION TANK

The vaporization tank and connections is shown in a schematic diagram, Figs. 1 and 3. The fuel and air were mixed and mixture vaporized in the tank. The temperature of the fuel-air mixture, which was held constant at 175 degrees Fahrenheit, was controlled by the circulation of ethyl glycol through heating coils. The temperature of the ethyl glycol was regulated

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The vaporization tank and connections is shown in a schematic diagram, Figs. 2 and 3. The fuel and air were mixed and mixture vaporized in the tank. The temperature of the fuel-air mixture, which was held constant at 175 degrees Fahrenheit, was controlled by the circulation of ethyl glycol through heating coils. The temperature of the ethyl glycol was regulated

by electric heating coils and steam circulation in a heating tank and by means of an improvised gas stove. The circulation of ethyl glycol was obtained by means of a small centrifugal pump.

A pipe leading from the vaporization tank to the safety valve contained a Y connection with connecting lines to open manometers for the measurement of the intake manifold pressure to the engine hereafter called (P_3) and when corrected for leakage error, (P_{3e}). (See Appendix "C")

OIL SYSTEM AND JACKET WATER SYSTEM

The oil system and jacket circulating water system are shown in a schematic diagram, Fig. 4. The jacket water temperature was held constant at 206 degrees Fahrenheit. The temperature was controlled by the circulation of water through a cooler between the condenser and the jacket. The oil temperature was held between 125 and 130 degrees Fahrenheit by means of circulating steam or cooling water through the two heat exchangers.

MEASURING INSTRUMENTS

The engine power output was absorbed by a Star electric cradle dynamometer. The brake torque was balanced by a hydraulic piston through a lever arm. The oil pressure on the piston was measured in inches of mercury on a manometer. This hydraulic system was so designed that one inch of mercury equaled one pound force acting on hydraulic piston. To extend

the manometer scale for high power, a counterweight was used to reduce the brake torque at the hydraulic cylinder. This manometer reading was then converted to pounds per square inch, brake mean effective pressure.

The dynamometer had a standard tachometer attached for rough determination of R.P.M. For fine indication of speed a strobotac was used to determine R.P.M. This consisted of a strobotac-lamp which illuminated 36 stripes painted on the engine flywheel.

The detonation pickup unit was a Draper flat diaphragm type having a natural frequency of about 95,000 cycles, described in Ref. 2. The output from this pickup was analyzed and projected on the screen of a cathode ray oscilloscope as a curve of relative rate of change of cylinder pressures against time. The oscilloscope was made by Allen B. DuMond Laboratories, Inc., model 208. When the condition of incipient detonation was reached this pressure curve showed a "pip" of high rate of change of pressure and high frequency about one third of the distance down the hump of the curve. Increase in intensity of detonation increased the height and width of this "pip". This indication proved accurate and easy to duplicate. The method is described in detail in Ref. 3.

The compression ratio was varied in the usual C.F.R. engine manner by raising or lowering the cylinder. The relative heights of the cylinder were measured by a micrometer built into the engine. A previous work had calibrated this micrometer against compression ratio by actually measuring the clearance

volume with water.

An M.I.T. balanced pressure indicator, described in Ref. 4 and 5, was used for obtaining heavy spring pressure-crank angle diagrams in conjunction with M.I.T. diaphragm pressure unit. A thin diaphragm, .0015 inches, was used in the diaphragm pickup. The heavy spring, 200 pounds per square inch, pressure-crank angle diagrams were converted into pressure volume indicator diagrams.

PROCEDURE

The determination of an iso-det line of incipient detonation for a fuel was made by using the manifold pressure as the dependent variable and varying the compression ratio until incipient detonation occurred. At that condition, the indicated mean effective pressure could be calculated and the iso-det point established. To eliminate the effect of the other operating conditions, all the tests were made with the following quantities constant within the tolerances shown:

1.	Revolutions per minute	1200 R.P.M.
2.	Piston speed	900 ft./min.
3.	Mixture temperature	$175 \pm 1^{\circ}$ F.
4.	Jacket cooling water temperature	$206 \pm 1^{\circ}$ F.
5.	Spark advance	30 degrees
6.	Inlet oil temperature	$127^{\circ} \pm 6^{\circ}$ F.
7.	Inlet oil pressure	46 ± 4 lb./in.^{2}

8. Incipient detonation

9. Fuel air ratio at best power

Fuel	Fuel Air Ratio	% Chemically Correct
Iso-octane	.0785 $\pm$ .0003	118
Triptane	.0779 $\pm$ .0002	118
Di-isobutylene	.0815 $\pm$ .0002	120
Ethyl benzene	.0883 $\pm$ .0002	120

The engine exhaust was discharged to the atmosphere through an exhaust surge tank. The supercharger air humidity was saturated at 65° F.

The choice of the above listed constants was made after discussions with Professor C. F. Taylor and Professor W. A. Leary, based on previous experimental work with the fuels used in this investigation and upon the conditions found during the familiarization runs.

Familiarization runs were conducted to check the engine, accessories, ane calibration curves, to determine the optimum operating conditions for the above listed constants, and as a general check on operating procedure and technique.

The procedure and quantities held constant, except for variation in the fuel air ratios to obtain best power for each fuel, were the same for the four fuels tested. The inlet manifold pressure in inches of mercury was varied from approximately 20 to 70 inches, with five points of incipient detonation determined for each fuel.

After the engine was started each day and before recorded runs were made, the engine was warmed up for one hour to stabilize all operating quantities and to allow the engine to reach thermal equilibrium. When a new recorded run of different manifold pressure was made, a period of one half an hour was allowed for all operating quantities to reach a steady state.

The general procedure used for each recorded run was to first make an approximation of the rate of fuel flow and rotameter setting calculated from the expected air consumption at the inlet manifold pressure to be tested, and from the fuel-air ratio of the fuel being tested. The inlet manifold and approximate rotameter setting were set to the desired quantity. The compression ratio was varied to give as near as possible incipient detonation; and a steady state established for all operating quantities. The air consumption, Ma, was then computed from the orifice measurements and any refinement necessary made in the rotameter setting. The compression ratio was varied through a very small range to obtain the most accurate point of incipient detonation. Readings were made on all measuring instruments periodically and all operating quantities were kept stabilized. After a period of steady state operation at the desired fuel air ratio and with the engine in thermal equilibrium, the point of incipient detonation was found and all measuring instruments were read and recorded.

Pressure-crank angle diagrams, shown in Figs. 5 and 6, were made over the range of brake loads obtained in the test runs with the M.I.T. balanced-pressure diaphragm type indicator using

a heavy spring of 200 pounds per square inch per inch and a diaphragm type pickup. All operating variables were held constant over a period of one-half hour before and during the making of the indicator cards.

From the pressure-crank angle diagrams, heavy spring indicator diagrams of pressure volume were drawn and indicated mean effective pressure calculated. A curve was drawn of brake mean effective pressure versus indicated mean effective pressure as obtained from the indicator cards and the brake loads. From the curve, the indicated mean effective pressure of all the test runs was obtained by entering the curve with the brake mean effective pressure calculated for the run and finding the corresponding indicated mean effective pressure.

RESULTS AND DISCUSSION

A composite record of the data sheets of the laboratory test runs 1 to 28 of the four fuels is shown in Table I. The Table contains the data from readings of the measuring instruments, shown in Fig. 2, the results computed from the recorded data, and the corrected results. The computed results include the following: air consumption, $\dot{M}a$; fuel-air ratio, F/A; brake mean effective pressure, bmep; and indicated mean effective pressure, imep. The methods used in calculating the air consumption, bmep, and imep, are shown in Appendix "B". The reasons for and method of calculating the corrected results, inlet manifold pressure, P_{3c}, and mass rate of flow of fuel-air mixture is shown in Appendix "C".

The recorded and computed data obtained from the heavy spring indicator diagram runs, modified form of runs 24 to 28, are shown in Table II. The modification to runs 24 to 28, for indicator data, consisted of the lowering of the compression ratio in order to operate the engine out of the incipient detonation region while the pressure-crank angle diagrams were being made. This changed the compression ratio, bmep, and imep. All other operating quantities were held the same as tabulated in Table I for runs 24 to 28. The heavy spring pressure crank angle diagrams, as recorded by the M.I.T. Indicator, and resulting pressure volume diagrams, are shown in Figs. 5 and 6. From the results calculated from the diagrams and recorded data and tabulated in Table II, a curve of imep vs. bmep was plotted as shown in Fig. 7.

Since the speed and engine operating quantities were held constant for all the runs at the same inlet manifold pressure, the friction mean effective pressure should be the same for all four fuels. Therefore, the imep, as tabulated in column 21, Table I, for all the test runs was taken from Fig. 7, by entering the curve with the bmep of the test run, column 20, Table I, and reading the corresponding imep.

The computed and corrected results (refer to Appendix "C") of the test runs, 1 to 28, for all four fuels, are tabulated in Table III. From the results as given in Table III, curves of compression ratio vs inlet manifold pressure (P_{3c}) for the four fuels were plotted as shown in Fig. 8. Each fuel produced an iso-det line (incipient detonation), which is the boundary between the detonation and non-detonation regions for that fuel. Any operating condition of the engine that falls above the iso-det line will be in the region of detonation. The higher above the iso-det line the operating point lies, the greater will be the detonation. Since inlet manifold pressure is not a direct measure of the power available to the cylinder, iso-det curves for each fuel were plotted for indicated mean effective pressure vs compression ratio as shown in Fig. 9. As in Fig. 8, any operating point above the iso-det curve of the fuel will be in a region of detonation.

It is seen from Figs. 8 and 9 that there is a slight difference in the curvature of each iso-det and in the relationship

of each iso-det line to the others. The reasons for the slight differences are as follows: one, the relationship between inlet manifold pressure (P_{3c}) and imep is not linear; and two, the compression ratios of the fuels are not the same. With a given relationship between inlet manifold pressure and air consumption, this produces variations in the relationship of air consumption to indicated mean effective pressure. As an example of the variation, a plot of air consumption vs imep ($\mathring{M}_{ac}$ vs IMEP) has been made in Fig. 10 for two fuels, di-iso-butylene (SR-10) and triptane. For the same air consumption the tests with triptane were run at higher compression ratios. This shows in Fig. 10, where for the same air consumption, triptane has a higher imep than di-iso-butylene.

From Figs. 8 and 9, it is noted that with other engine operating quantities held constant, all four fuels tend to detonate more as the imep increases, as the inlet manifold pressure increases, or as the compression ratio increases. This follows previous experimental work and theory.

Iso-octane is the most sensitive to change in inlet manifold pressure. At very low inlet manifold pressures, or imep, iso-octane closely approaches the results obtained from triptane. As the imep is increased, iso-octane becomes poorer in anti-detonation quality. The three other fuels, triptane, di-iso-butylene, and ethyl benzene, have approximately the same slopes in the curves, showing that all three are about equal in sensitivity to changes in inlet manifold pressure and imep.

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Triptane appears to be the superior fuel for anti-detonation qualities and characteristics within the range of inlet manifold pressure and indicated mean effective pressure at the speed of 1200 RPM, an inlet mixture temperature of 175°F., and at the best power fuel-air ratio used in this investigation. Ethyl benzene closely approaches triptane at high and low imep, as does iso-octane at low values. However, in the range of compression ratios used in present aircraft engines of about 6.5, and assuming the detonation characteristics of the fuels are the same in a full scale aircraft engine, triptane, as compared to iso-octane, can allow an increase in compression ratio at 7.5 in a future engine at the same imep as iso-octane without detonation. Similarly, for a constant compression ratio of 6.5, a change of fuel from iso-octane to triptane increases the allowable iso-det imep from 164 to 226 psi., an increase of 37.4 percent. The four fuels have indicated powers (imep) at the compression ratio of 6.5 as follows:

Fuel	imep	Percent
a. Triptane	226	37.4
b. Ethyl benzene	204	24.0
c. Iso-octane	164	0
d. Di-iso-butylene	130	-20.5

This order of importance holds for compression ratios up to about 8.8.

These relationships of the four fuels are effectively altered by variation of the engine operating conditions that were held constant in this investigation. Reference 8 shows the effect of changes of engine speed and intake mixture temperature, and the addition of tetra-ethyl lead to the fuel on the detonation characteristics of the four fuels used in this investigation. Whereas the engine speed was held constant at 1200 RPM in this investigation, Ref. 8 shows that increasing the engine speed increases the critical compression ratio of iso-octane while the three other fuels show a decrease in critical compression ratio. This effect would place iso-octane in a more favorable position as compared to the other fuels as the engine speed is increased above 1200 RPM. Triptane and di-isobutylene have about the same drop in critical compression ratio while ethyl benzene has about twice the drop of the other two for the same increase in engine speed.

The effect of increase in inlet mixture temperature was to decrease the critical compression ratio for all four fuels. However, iso-octane was affected the least. Triptane and di-isobutylene showed a decrease of about four times that of iso-octane, and ethyl benzene showed about five times the minimum decrease. Again iso-octane would improve relative to the other three fuels with increase in inlet temperature.

The addition of tetra-ethyl lead to these fuels had the effect of increasing their critical compression ratios, but to

different degrees. Iso-octane showed the greatest increase in critical compression ratio whereas the other three fuels showed a lesser increase. In all three cases of change of engine operating conditions, iso-octane showed either the greatest improvement or the least deterioration.

However, when an attempt is made to compare the results of Ref. 8 and of this investigation, caution must be taken. The variation of engine speed, inlet temperature, and addition of tetra-ethyl lead are only superficial measurements of the situation. Thus, until the pressure-temperature-time history of the unburned charge is known for both sets of results and used as a basis of comparison, the only conclusion to be made is that the three fuels, triptane, di-iso-butylene, and ethyl benzene show a marked family similarity both in the results of this investigation and those of Ref. 8.

It was found in the investigation that ethyl benzene is difficult and dangerous to handle and operate in the engine. In addition, the ethyl benzene readily attacks neoprene and lucite. It was also known that di-iso-butylene is not reliably stable for prolonged storage.

CONCLUSIONS

The results of this investigation give the following conclusions:

1. All four fuels tend to detonate more as:
   (a) The inlet manifold pressure is increased.
   (b) The imep is increased.
   (c) The compression ratio is increased.
2. Iso-octane is the most sensitive to changes in inlet manifold pressure and imep.
3. Triptane, di-iso-butylene, and ethyl benzene have approximately the same sensitivity to changes in inlet manifold pressure and imep.
4. Triptane is superior to the other fuels in anti-detonation characteristics.
5. Triptane, di-iso-butylene and ethyl benzene show a marked family similarity in their detonation characteristics.

APPENDIX "A"

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APPENDIX "B"

Appendix "B"

SAMPLE CALCULATIONS

Table I

A. Inlet manifold pressure, P_3 , inches of mercury.

$P_3 = P_o/25.4 \pm \Delta P_3$ $\qquad$ P_o mm. hg.
ΔP_3 in. hg.
p_3 in. hg.

$P_{3c} = P_3$ and curve of Fig. 12.

Columns 1 to 6
Example, run 2.

$$P_3 = 50.0 = 757.6/25.4 + 20.2$$

$$P_{3c} = f(50.0) = 52.0 \text{ in. hg.}$$

B. Air consumption, M .

$$\dot{M}_a = 1.095 \sqrt{\frac{\Delta P_2 P_1}{T_1}}$$

$$P_1 = P_o/25.4 \pm \Delta P_1$$

Columns 7 to 11
Example, run 2.

P_1 52.4 29.8 22.6

$$\dot{M}_a = 1.39 = 1.095 \sqrt{\frac{17 \times 52.4}{551}} \quad \text{lbs./min.}$$

$\dot{M}_{a_c} = \dot{M}_a$ and curve of Fig. 12.

C. Fuel-air ratio F/A.

$$F/A = \dot{W}_f / \dot{M}_a$$

Columns 11 , 14 to 16
Example, run 2,

$$F/A = .0785 = .109/1.39$$

D. IMEP

$bmep = 4.25\ f$

$f = 20 + .7225\ W + S_3$

$imep = \phi(bmep)$ (Fig. 7)

Columns 17 TO 21
Example, run 2.

$f = 39.53 = 20 + .7225 \times 9.87 + 12.4$

$bmep = 167.8 = 4.25 \times 39.53$ psi

$imep = 207 = \phi(167.8)$ psi

Table II

Computation of imep.

$$imep = \frac{\text{area of diagram, sq. in.}}{\text{length of diagram, inches}} \times X$$

$imep = area \times 200/5 = 40 \times$ area of diagram

Example, run 28.

$imep = 40 \times area = 40 \times 1.95 = 78$ psi

APPENDIX "C"

APPENDIX "C"

DETERMINATION OF INTAKE MANIFOLD PRESSURE AND AIR CONSUMPTION CORRECTIONS

At the conclusion of the di-iso-butylene test, run 18, the periodic check of manometer leads showed a small hole in the tubing of the negative pressure water manometer, one of the vaporization tank manometers on a common Y correction, Fig. 3. This particular manometer was not used during the tests; but such a leak would bleed off fuel-air mixture and also produce an error in the other manometer that was on the common Y connection and measured ΔP_3. Consequently, a plot of air consumption ($\dot{M}_a$) against imep was made for runs 15 to 18 in Fig. 10. This curve indicated that the leak had been present throughout these runs. A series of check runs was made, runs 20 to 23, with the same fuel but without the leak. The operating conditions were the same as in the first set of runs, runs 15 to 18. The correction of the leak changed the air consumption, the inlet manifold pressure manometer reading, ΔP_3, and the bmep as shown in Table I. This second set of runs was plotted in Fig. 10, and produced the desired straight line function between air consumption and imep that indicated a correct measurement of engine intake conditions. In Fig. 10, at constant imep, the difference between the curve of the first set of runs ($\dot{M}_a$ vs IMEP) and the curve of the second set of runs ($\dot{M}_{ac}$ vs IMEP) was the error in air consumption caused by the leak.

To determine the effect of the leak on inlet manifold pressure, P_3 (P_3 equals P_o plus ΔP_3) the first set of runs was plotted in Fig. 11 as inlet pressure against air consumption. This curve was then corrected for the air consumption error determined in Fig. 10 to produce a new curve (P_3 vs $\mathring{M}_{ac}$). The second set of runs was also plotted in Fig. 11 (P_{3c} vs $\mathring{M}_{ac}$) and is correct for both air consumption and inlet pressure. In Fig. 11, at constant air consumption, the difference between the corrected curve of the first set of runs (P_3 vs $\mathring{M}_{ac}$) and the curve of the second set of runs (P_{3c} vs $\mathring{M}_{ac}$) is the error in intake manifold pressure. These two errors determined in Figs. 10 and 11 were then used to plot the correction curves of Fig. 12, and the first set of runs 15 to 18 were corrected with this curve.

The question of how many runs were affected by the leak was answered by plotting runs 1 to 14 for air consumption against imep. These runs showed a similar deviation from the straight line function, as was also shown by runs 15 to 18. Therefore, the errors due to the leak were present in the data for runs 1 to 14. The correction curves of Fig. 12 were considered applicable and were used to correct the data of runs 1 to 14.

These errors in air consumption for runs 1 to 18 indicated a possible corresponding error in fuel-air mixture received by the engine. However, the location of the leak in the manometer line leading from the Y connection was in such a position rela-

tive to the engine intake that at vaporization tank pressures above atmospheric, completely mixed fuel and air were bled away from the engine intake. This meant that no error in fuel-air ratio was produced by the leak when P_3 was greater than 30 inches of mercury. When the vaporization tank pressure was less than atmospheric, the leak bled outside air directly into the engine intake, thereby diluting the fuel-air mixture. Therefore, when P_3 was less than 30 inches of mercury, the fuel-air ratio was less than the desired best power ratio. The result was that the curves of Figs. 8 and 9 for iso-octane, di-iso-butylene, and ethyl benzene have a small error in curvature at the end where P_3 is less than 30 inches of mercury.

An approximation of the correct curve for these three fuels for best power fuel-air ratio was made by using the data point from run 19, which is at best power fuel-air ratio, and comparing the change in the curve from the corresponding diluted fuel-air ratio data point of run 17 on Fig. 8. A similar correction was approximated for the curves of iso-octane and ethyl benzene and is shown in Fig. 8 by a light curve for diluted fuel-air ratio and a heavy curve for best power fuel-air ratio for each of the three fuels.

APPENDIX "D"

TABLE I DATA SHEET OF DETONATION CHARACTERISTICS OF FUELS

M.I.T. AERO ENGINE LABORATORY

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
FUEL				P_0	P_0	ΔP_3	P_3	P_{3c}	ΔP_1	P_1	ΔP_2	T_1	$\dot{M}_a$	S_1	r	S_2	$\dot{M}_f$	F/A	S_3	W	$\mathcal{F}$	BMEP	IMEP	S_4	S_5	T_3	T_2	T_4	P_4	T_5	ΔP_5
	DATE		RUN	mm hg	IN hg	IN hg	IN hg	IN hg	IN hg	IN hg	IN H_2O	°F ab	LB/MIN	IN.	RATIO	UNITS	LB/MIN	RATIO	IN hg	LBS.	LBS.	P.S.I.	P.S.I.	RPM	DEG.	°F	°F	°F	P.S.I.	°F	IN H_2O
ISO-OCTANE	3/15	*	1	760.7	30.3	0	30.0	30.0	0	30.0	6.86	544.5	0.685	.163	7.79	11.25	.0535	.0782	0.95	0	20.95	89	119	1200	30	175	206	126	46	83	4
	3/22	*	2	757.6	29.8	20.2	50.0	52.0	22.6	52.4	17.0	551	1.390	.474	5.62	17.5	.1090	.0785	12.4	9.87	39.53	167.8	207	1200	30	174	207	126	49	83	5
	3/26	*	3	760.7	30.0	30.0	60.0	62.4	31.3	61.3	21.5	549	1.718	.610	5.05	19.8	.1340	.0782	18.3	12.56	47.36	201	249.4	1200	30	170	203	125	42	80	6
	3/28	*	4	756.8	29.8	30.2	60.0	62.4	33.2	63.0	21.4	551	1.705	.653	4.90	19.7	.1336	.0785	18.3	12.56	47.36	201	249.4	1200	30	174	206	134	42	89	6
	3/28	*	5	756.8	29.8	20.2	50.0	52.0	22.7	52.5	16.7	550	1.380	.493	5.53	17.3	.1080	.0785	10.1	12.56	39.06	166	206	1200	30	175	205	132	44	88.5	5
	3/28	*	6	756.8	29.8	10.2	40.0	41.4	12.5	42.3	12.3	548	1.065	.340	6.36	14.6	.0838	.0785	2.0	12.56	31.06	132	168	1200	30	175	206	134	45	88	4.5
	3/28	*	7	756.8	29.8	-9.8	20.0	19.2	-0.2	29.6	1.77	542	0.340	.020	9.65	7.6	.0267	.0785	-8.8	0	11.02	47.6	79	1200	30	174	206	124	49	85	4
ETHYL BENZENE	4/3	*	8	758.9	29.8	20.2	50.0	52.0	22.4	52.2	15.4	538	1.338	.327	6.44	19.0	.1205	.0901	10.2	12.75	39.40	167.3	207.5	1200	30	175	205	126	43	78	5
	4/3	*	9	758.9	29.8	10.2	40.0	41.4	11.8	41.6	11.7	537	1.040	.248	7.02	16.1	.0917	.0882	1.45	12.75	30.66	130.4	166.2	1200	30	175	206	123	45	69	4.5
	4/4	*	10	760.6	29.9	27.5	57.4	59.6	30.1	60.0	18.7	541	1.574	.369	6.18	20.25	.1385	.0880	16.5	12.75	45.71	194.2	240.0	1200	30	175	206	125	44	81	5.5
	4/4	*	11	760.6	29.9	20.1	50.0	52.0	22.45	52.35	15.9	540	1.352	.324	6.46	18.85	.1190	.0882	9.8	12.75	39.01	166.0	206.0	1200	30	175	205	121	48	82	5.0
	4/4	*	12	760.6	29.9	10.15	40.05	41.5	11.8	41.7	11.7	539.5	1.040	.235	7.13	15.9	.0918	.0883	1.0	12.75	30.21	128.5	163.8	1200	30	175	205	125	43	82	4.5
	4/4	*	13	760.6	29.9	0.1	30.0	30.0	0.94	30.84	6.63	539	0.674	.130	8.14	12.4	.0595	.0883	-8.25	12.75	20.45	87.0	116.6	1200	30	175	206	120	46	81	4.0
	4/4	*	14	760.6	29.9	-10.0	19.9	19.1	0	29.9	1.63	536	0.330	.045	9.26	8.4	.0291	.0883	-8.5	0	11.5	49.0	80.0	1200	30	175	205	126	44	82	4.0
DI-ISOBUTYLENE SR-10	4/8	*	15	761.8	30.0	20.00	50	52.0	22.40	52.40	16.00	535	1.370	.529	5.37	18.00	.1118	.0815	10.10	12.75	39.31	167.00	207.2	1200	30	175	205	126	42	82	5
	4/8	*	16	761.8	30.0	10.00	40	41.4	11.90	41.90	12.25	538	1.070	.426	5.86	15.20	.0873	.0815	0.95	12.75	30.16	128.00	163.2	1200	30	175	205	128	43	82	4.5
	4/9	*	17	755.8	29.75	-9.75	20	19.2	0	29.75	1.71	534	0.338	.158	7.84	7.90	.0275	.0815	-9.30	0	10.70	45.50	77.2	1200	30	175	206	127	47	76	4
	4/9	*	18	755.8	29.75	+0.25	30	30.0	1.25	31.00	7.00	539	0.694	.279	6.78	11.65	.0565	.0815	+0.80	0	20.80	88.40	118.3	1200	30	175	205	120	50	76.5	4
	4/15		19	752.9	29.60	-9.60	20	20.0	0.06	29.66	2.91	539	0.438	.158	7.84	9.00	.0360	.0816	-9.00	0	11.00	46.75	78.1	1200	30	175	205	127	44	81	4
	4/15	Δ	20	752.9	29.6	-9.60	20	20	0.06	29.66	2.96	539	0.441	.159	7.83	9.00	.0360	.0816	-9.00	0	11.00	46.75	78.1	1200	30	175	206	127	45	81	4
	4/15	Δ	21	752.9	29.6	10.40	40	40	11.17	41.30	9.75	547	0.939	.426	5.86	14.05	.0765	.0815	-0.40	12.75	28.80	122.30	157.0	1200	30	175	206	125	42	82	4.5
	4/15	Δ	22	752.9	29.6	20.40	50	50	22.00	51.60	12.30	540	1.185	.525	5.39	16.35	.0966	.0815	+7.90	12.75	37.10	157.50	196.7	1200	30	175	205	127	45	83	5
	4/15	Δ	23	752.9	29.6	0.40	30	30	1.35	30.95	6.80	540	0.684	.285	6.73	11.50	.0560	.0819	-8.50	12.75	20.70	88.00	118.0	1200	30	175	206	132	46	83	4
TRIPTANE	4/22		24	768.6	30.2	-0.2	30	30	0.75	30.95	6.67	544	0.675	.098	8.53	11.55	.0525	.0779	-8.35	12.75	20.85	88.5	118.5	1200	30	175	206	130	45	83	4
	4/23		25	762.3	30.0	30.0	60	60	31.90	61.90	14.80	542	1.422	.366	6.20	18.10	.1107	.0779	+17.8	12.75	48.00	204.0	253.2	1200	30	175	206	130	45	86	6
	4/23		26	762.3	30.0	20.0	50	50	21.65	51.65	12.40	546	1.855	.280	6.77	16.10	.0922	.0779	9.7	12.75	38.90	165.5	205.5	1200	30	175	206	128	45	87	5.5
	4/23		27	762.3	30.0	10.0	40	40	11.30	41.30	9.60	546	0.932	.189	7.53	13.90	.0725	.0779	0.8	12.75	30.00	127.5	162.5	1200	30	175	206	127	46	87	5
	4/24		28	759.2	29.8	-9.8	20	20	0.10	29.90	2.85	542	0.433	.017	9.71	9.05	.0338	.0779	-9.1	12.75	10.90	46.4	78.5	1200	30	175	206	120	49	84	4

* Runs 1 to 18 had error in ΔP_3 and $\dot{M}_a$ measurements which are corrected in column 6..

Δ Runs 20 to 23 were made under same conditions as Runs 15 to 18 but with P_3 (Manifold Pressure) correctly determined.
Runs 20 to 23 were used only for the Manifold Pressure (P_3) correction curve and $\dot{M}_a$ correction curve.

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TABLE II INDICATOR CARD DATA

FUEL - TRIPTANE, SPRING - 200 LBS.

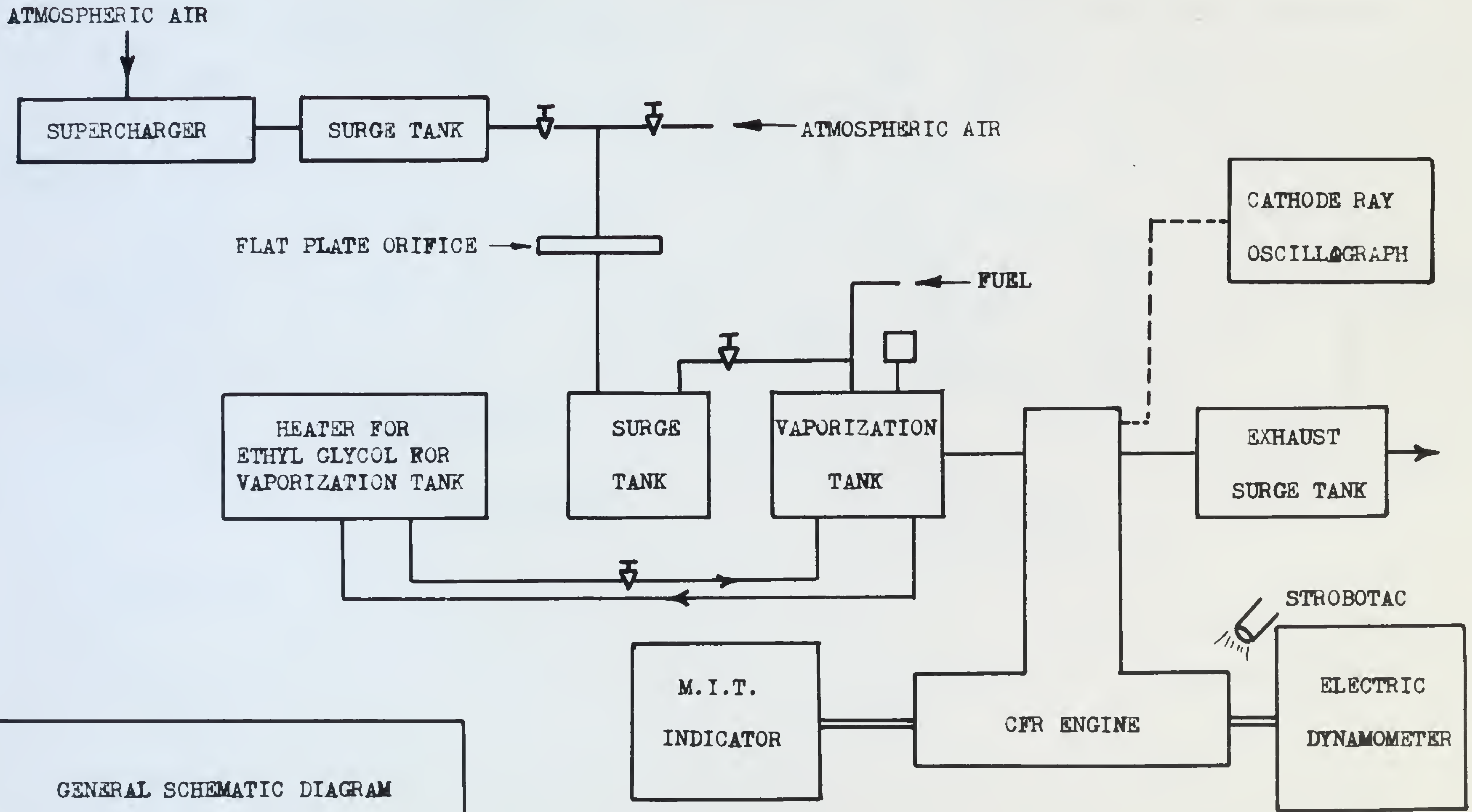
REF. FIGS. 5 & 6, TAB. I

1	2	3	4	5	6	7	8
RUN	P_{3c}	S_3	W	f	bmep	DIAG. AREA	IMEP
	IN. hg.	IN. hg.	LBS.	LBS.	P.S.I.	Sq. IN.	P.S.I
28	20	-9.1	0	[illegible]	46.4	1.95	70
24	30	-8.7	12.75	20.5	87.3	2.92	117
27	40	+0.5	12.75	21.7	120	[illegible]	[illegible]
26	50	1.4	12.75	[illegible]	164	4.10	[illegible]
25	60	17.4	12.75	[illegible]	198	[illegible]	245

[illegible] 5/46

TABLE III DATA USED FOR PLOTTING CURVES OF FIGURES 7 TO 12

1	2	3	4	5	6	7	8	9
FUEL	RUN	P_3	P_{3c}	$\dot{M}_a$	$\dot{M}_{ac}$	$\dot{M}_{ac}$	IMEP	μ
		IN. hg.	IN. hg.	LBS/MIN	LBS/MIN	LBS/HR.	PSI	
ISO-OCTANE	1	30	30.0	0.685	0.685	41.10	119.0	7.79
	2	50	52.0	1.390	1.264	75.84	207.0	5.62
	3	60	62.4	1.718	1.571	94.26	249.4	5.05
	4	60	62.4	1.705	1.558	93.48	249.4	4.90
	5	50	52.0	1.380	1.254	75.24	206.0	5.53
	6	40	41.4	1.065	0.980	58.80	168.0	6.36
	7	20	19.2	0.340	0.44[illegible]	26.52	79.0	9.35
ETHYL BENZENE	8	50	52.0	1.338	1.218	73.08	207.5	6.44
	9	40	41.4	1.040	0.960	57.60	166.2	7.02
	10	57.4	59.6	1.574	1.4[illegible]6	86.16	240.0	6.18
	11	50	52.0	1.352	1.230	73.80	206.0	6.46
	12	40.05	41.5	1.040	0.960	57.60	16[illegible]	7.13
	13	30	30.0	0.674	0.680	40.80	116.6	8.14
	14	19.9	19.1	0.330	0.438	26.40	80.0	9.26
DI-ISOBUTYLENE SR-10	15	50	52.0	1.370	1.246	74.76	207.2	5.37
	16	40	41.4	1.070	0.982	58.92	163.2	5.86
	17	20	19.2	0.338	0.440	26.40	77.2	7.84
	18	30	30.0	0.694	0.694	41.64	118.3	6.78
	19	20	20.0	0.438	0.438	26.28	78.1	7.84
	20	20	20	0.441	0.441	26.46	78.1	
	21	40	40	0.939	0.939	56.34	157.0	
	22	50	50	1.185	1.185	71.10	196.7	
	23	30	30	0.684	0.684	41.04	118.0	
TRIPTANE	24	30	30	0.675	0.675	40.50	118.5	8.53
	25	60	60	1.422	1.422	85.32	253.2	6.20
	26	50	50	1.185	1.185	71.10	205.5	6.77
	27	40	40	0.932	0.932	55.92	162.5	7.53
	28	20	20	0.433	0.4[illegible]	25.98	78.2	9.71



GENERAL SCHEMATIC DIAGRAM

OF

APPARATUS

FIGURE 1

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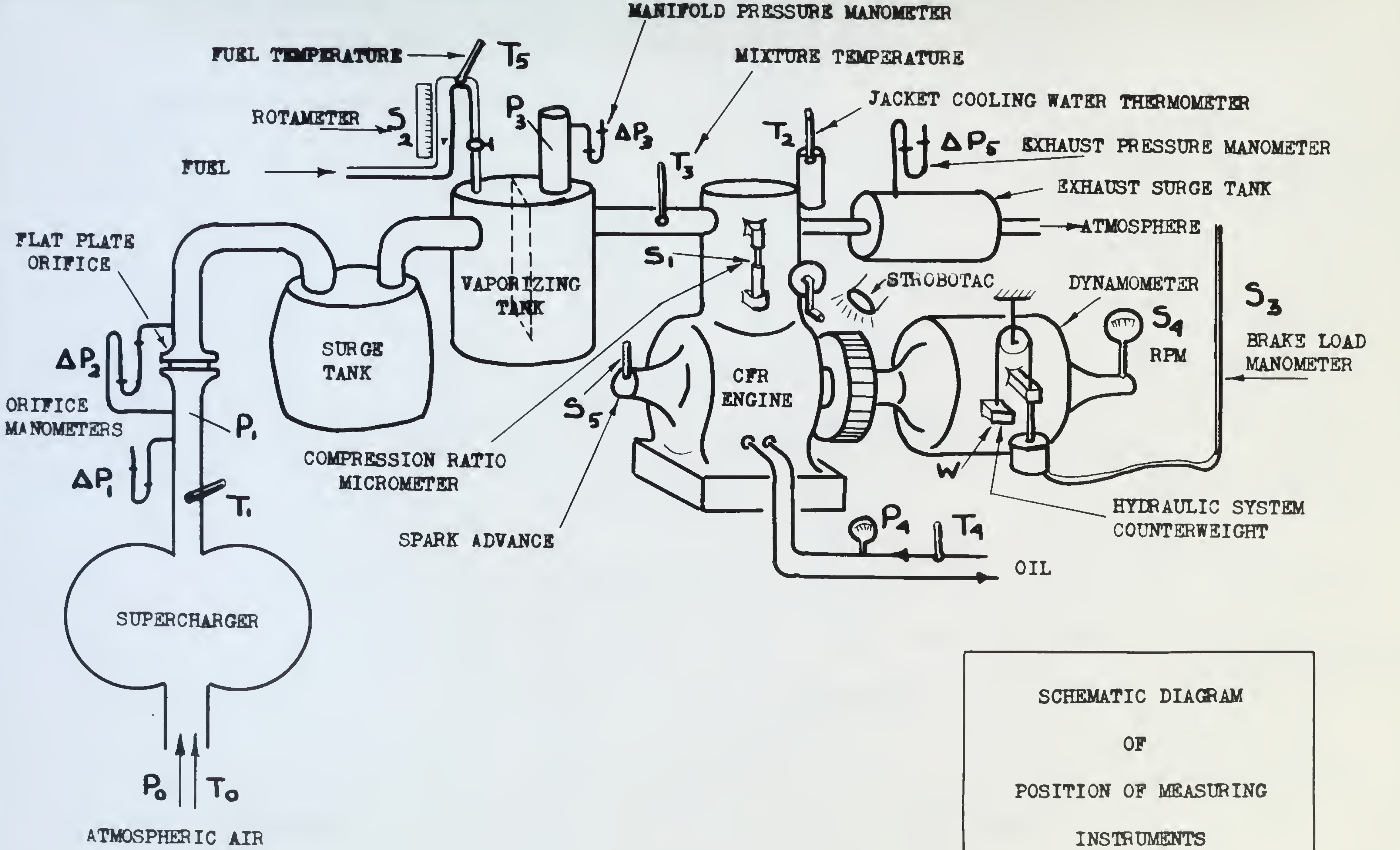


SCHEMATIC DIAGRAM

OF

POSITION OF MEASURING

INSTRUMENTS

FIGURE 2

GH 5/46

SCHEMATIC DIAGRAM

OF

C.F.R. ENGINE AND ACCESSORIES

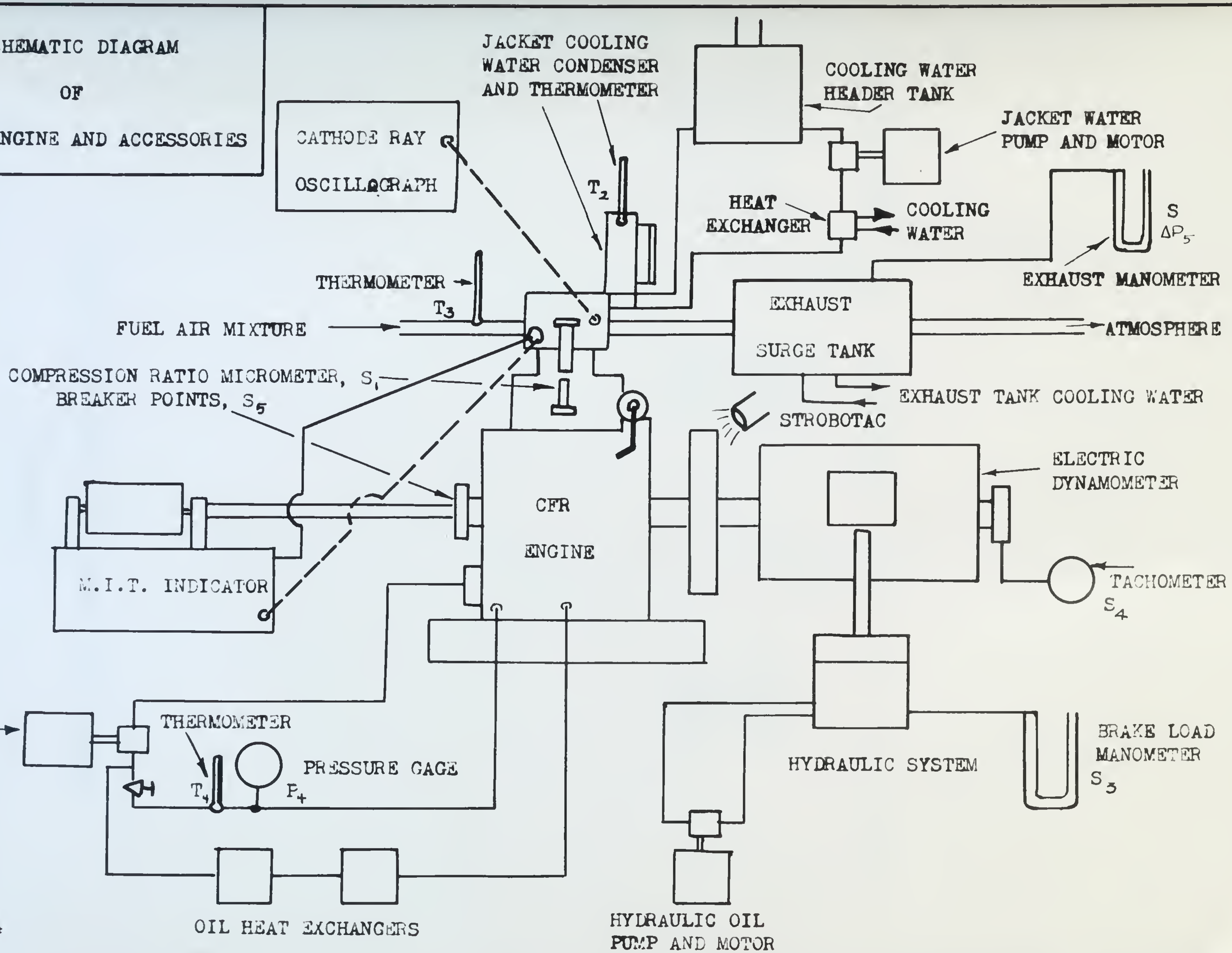
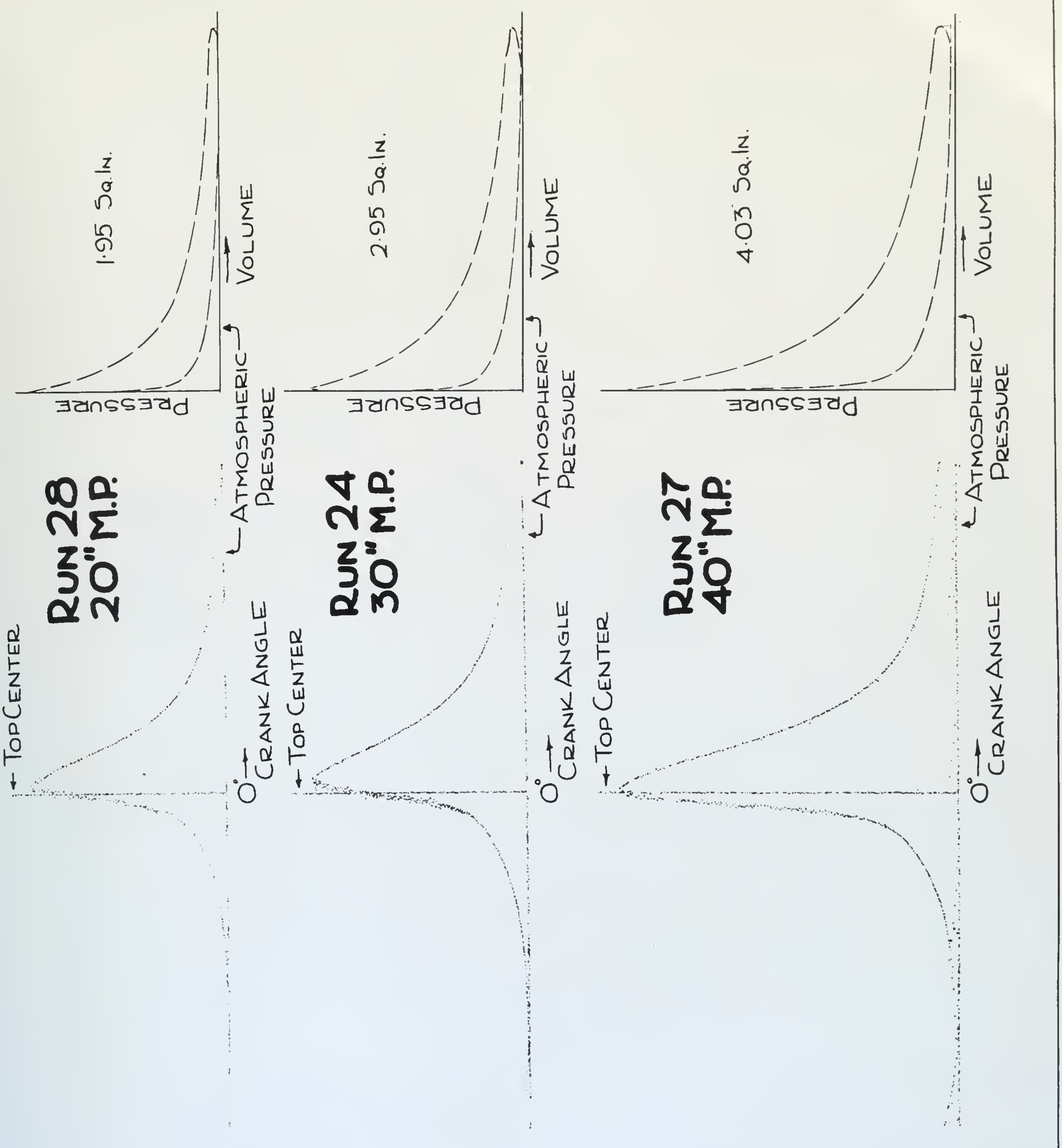


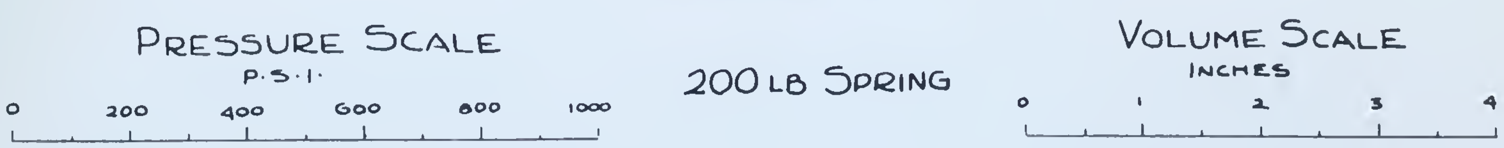
FIGURE 4

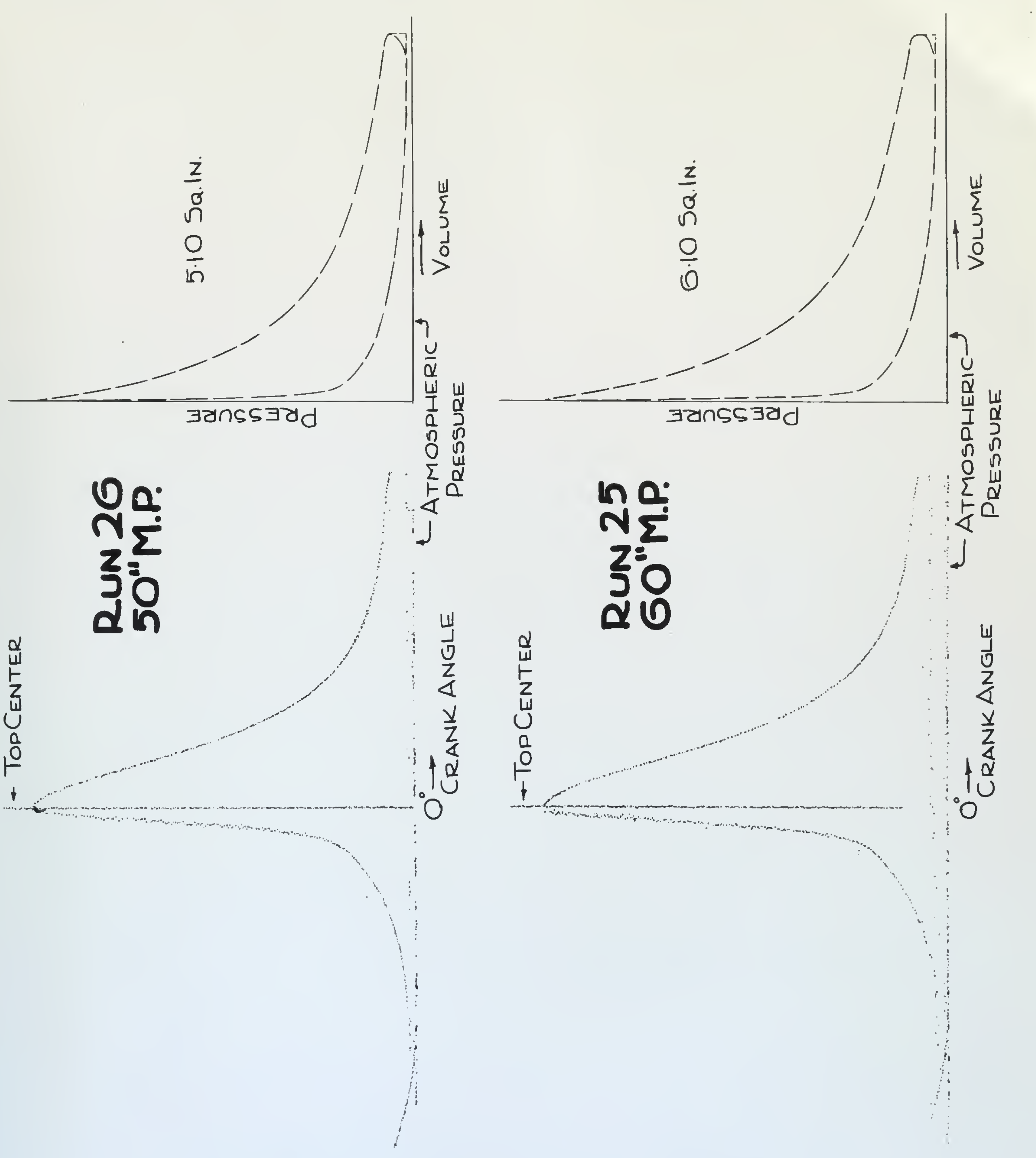
HC 5/46



Heavy Spring Indicator Cards

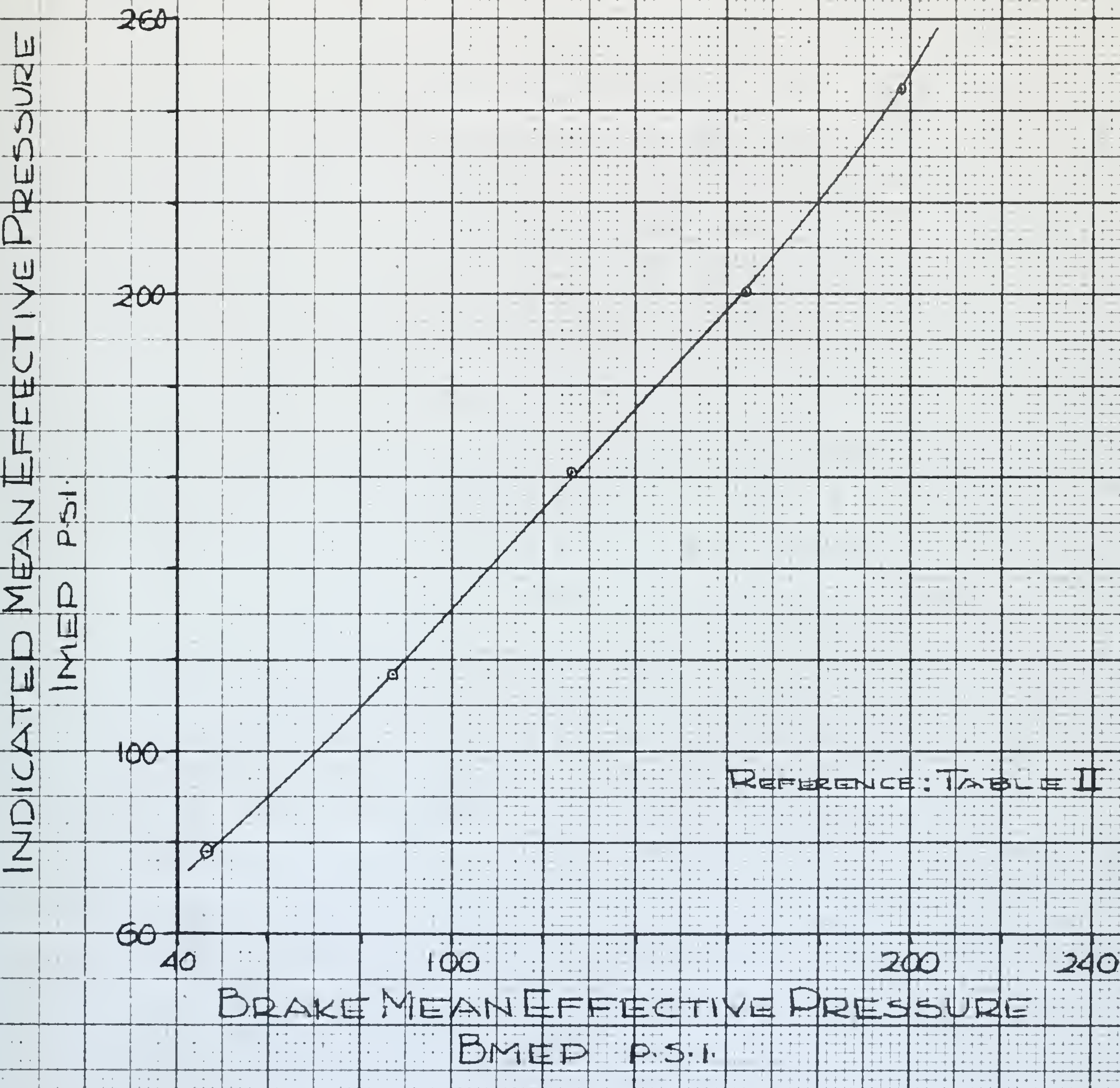
Figure 5





Heavy Spring Indicator Cards

Figure G



Variation of Imep with Bmep
C.F.R. Engine 1200 R.P.M.

Figure 7

G-H 4-46

BANKNOTE" NO. 174 K & E CO. N.Y. 40991

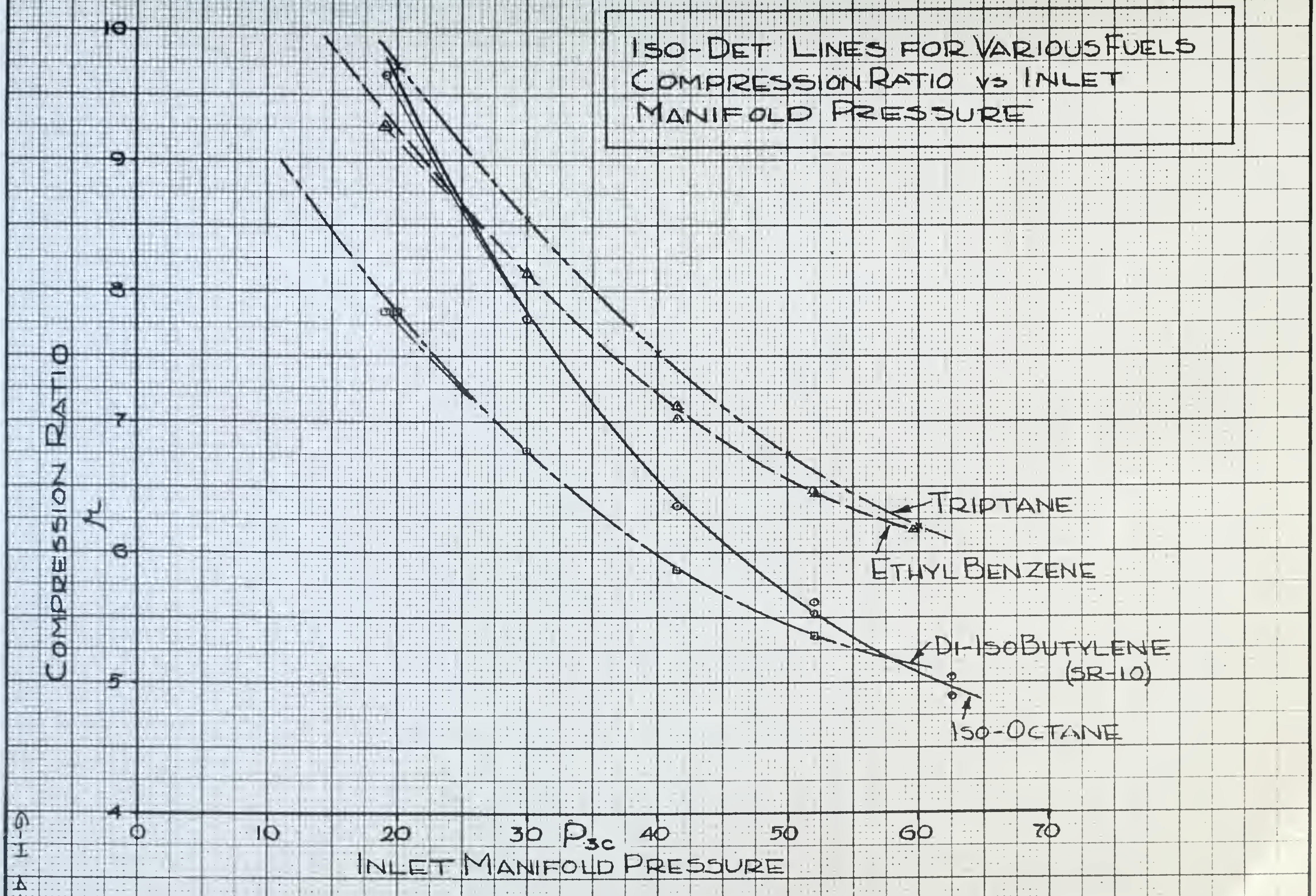
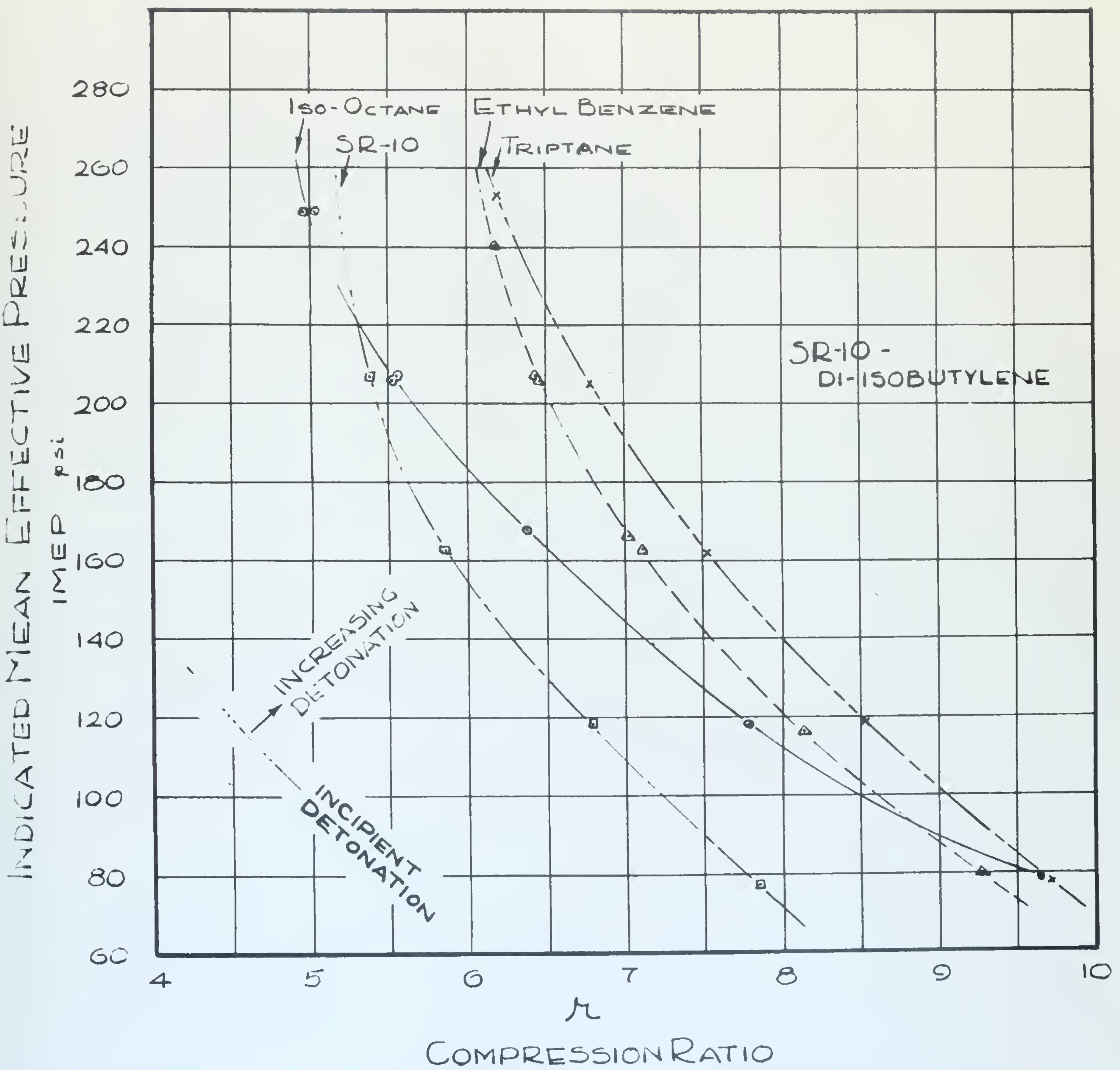


Figure 8

6-1 4-46



ISO-DET LINES FOR VARIOUS FUELS
IMEP vs COMPRESSION RATIO FOR
INCIPIENT DETONATION
PISTON SPEED 900 FT/MIN; 1200 RPM

FIGURE 9

G.H. 4-46

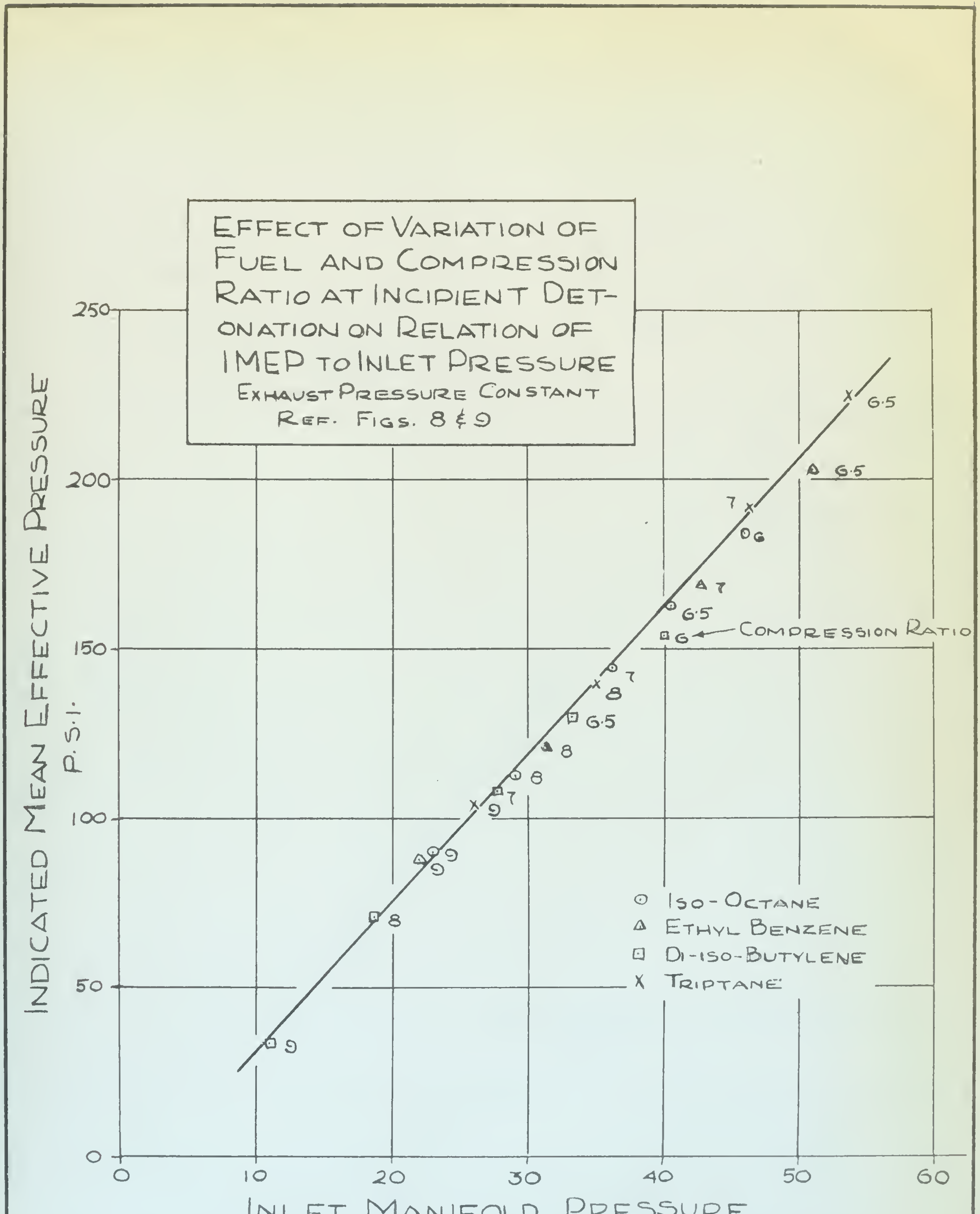


FIGURE 9a

G-H 5-46

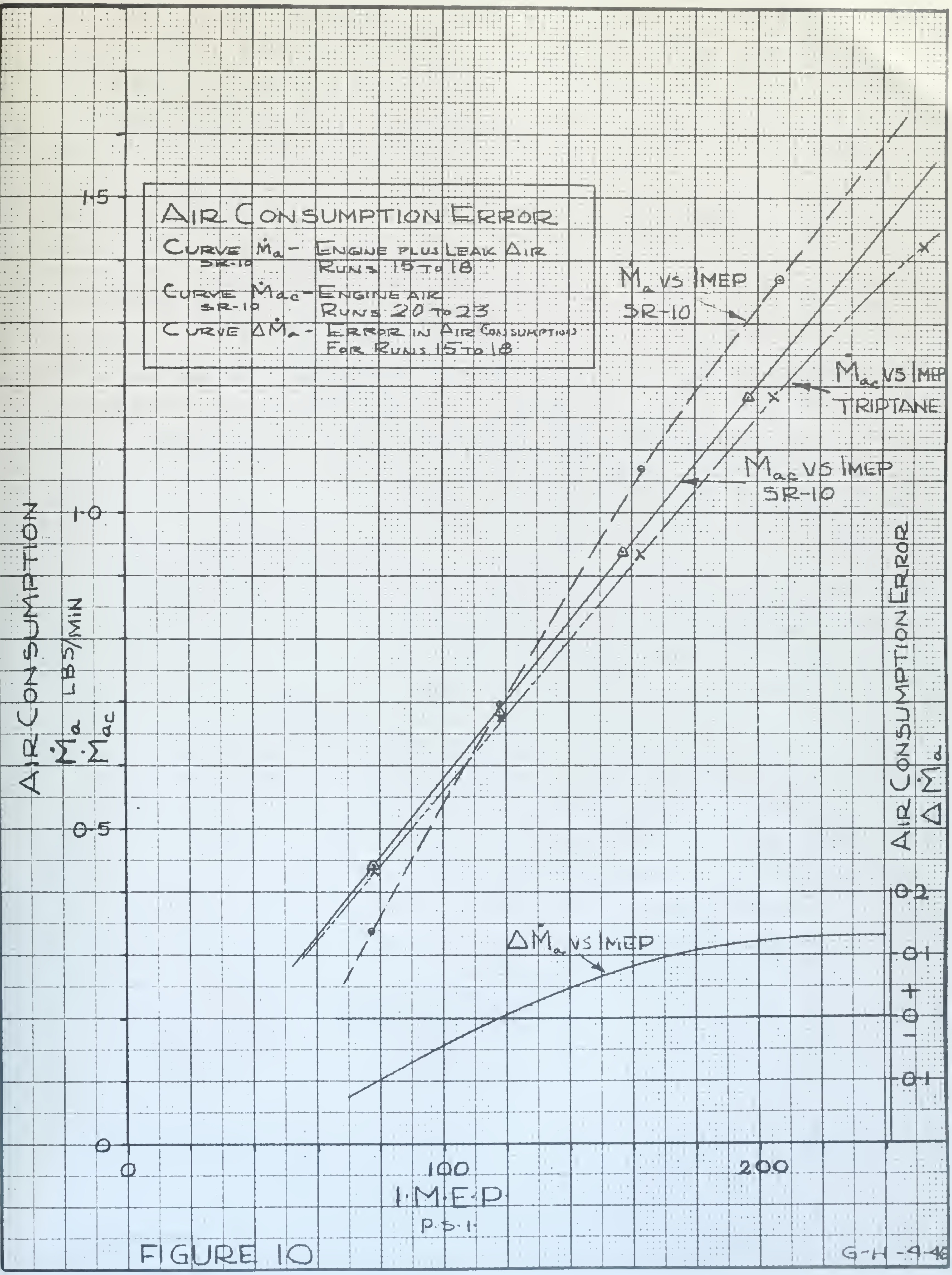


FIGURE 10

G-H-9-46

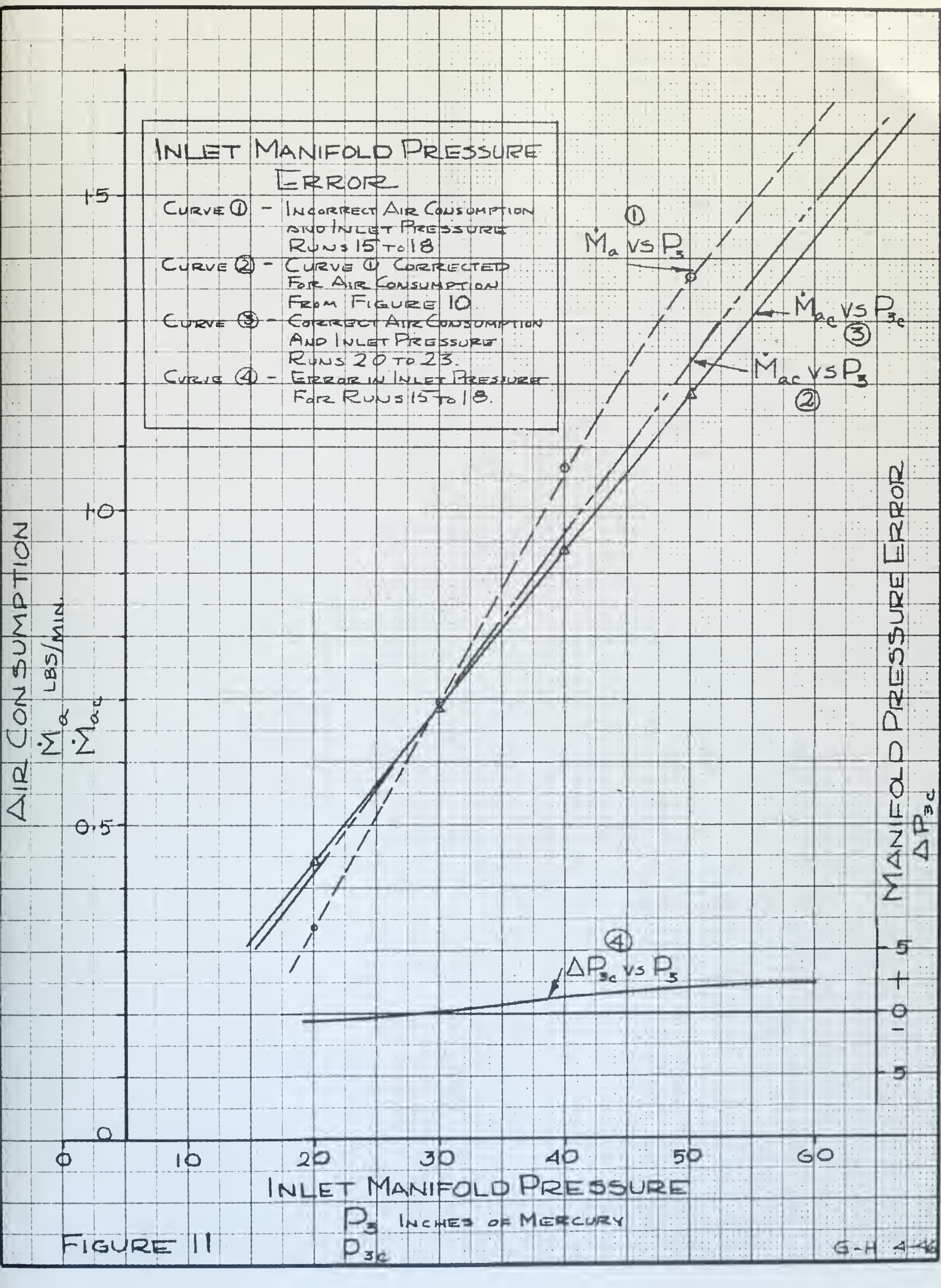


FIGURE 11

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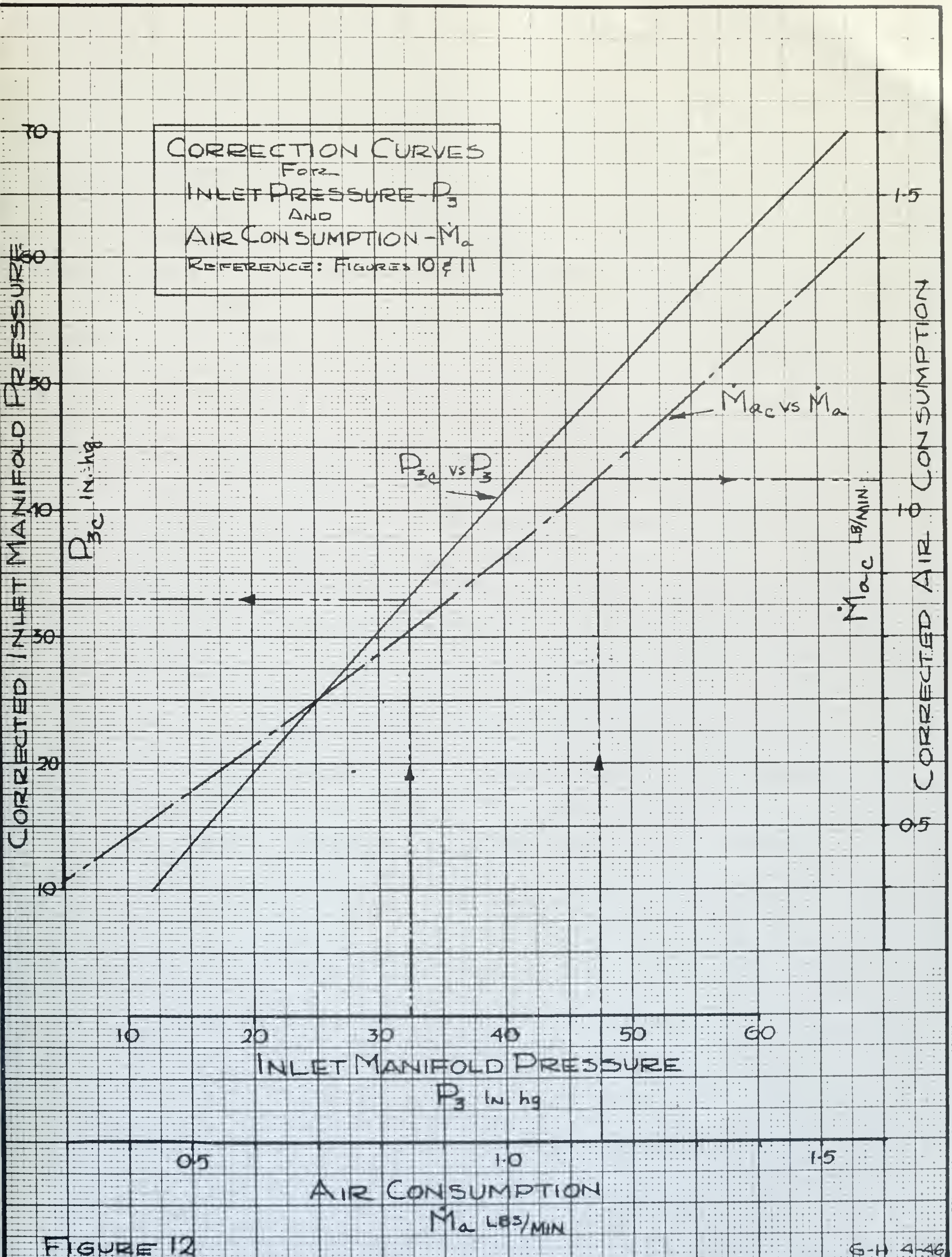

CORRECTION CURVES
FOR
INLET PRESSURE - P_3
AND
AIR CONSUMPTION - $\dot{M}_a$
REFERENCE: FIGURES 10 & 11
$\dot{M}_{ac}$ VS $\dot{M}_a$
P_{3c} VS P_3
CORRECTED INLET MANIFOLD PRESSURE
P_{3c} IN. hg
CORRECTED AIR CONSUMPTION
$\dot{M}_{ac}$ LB/MIN.
INLET MANIFOLD PRESSURE
P_3 IN. hg
AIR CONSUMPTION
$\dot{M}_a$ LBS/MIN
10
20
30
40
50
60
70
0.5
1.0
1.5
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FIGURE 12

Th
H2

Thesis 15487
H24 Harkleroad

Investigation of
detonation characteris-
tics of various fuels.